2-22-1999

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AIP | Applied Physics Letters

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Citation: Applied Physics Letters **74**, 1159 (1999); doi: 10.1063/1.123473
View online: http://dx.doi.org/10.1063/1.123473
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/74/8?ver=pdfcov
Published by the AIP Publishing

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(Received 26 May 1998; accepted for publication 11 December 1998)

The effect of the matrix material on the magnetostriction of composites containing highly magnetostrictive particles has been studied. Experimental results showed that the elastic modulus of the matrix is an important factor determining the bulk magnetostriction of the composite. For a series of composites with the same volume fraction of magnetostrictive particles but different matrix materials, the bulk magnetostriction was found to increase systematically with decreasing elastic modulus of the matrix. A model theory for the magnetostriction of such composites has been developed, based on two limiting assumptions: uniform strain or uniform stress inside the composite. The theory was then used to predict the magnetostriction of the entire material from the volume fractions of the components, their elastic moduli and magnetostrictions. These predictions were in agreement with the experimental results. It is concluded that to obtain a high magnetostriction and adequate mechanical properties of a composite, the elastic moduli of the magnetostrictive phase and the matrix should be as close as possible in value. © *1999 American Institute of Physics.* [S0003-6951(99)03106-X]

There has recently been interest in the development of magnetomechanical torque sensors[1–3] because of the sensitivity of magnetic properties to torsional stress. Clark[4] and Greenough[5] have discussed rare-earth-iron compounds, however the high cost and brittleness of these materials restrict applications. Composites of highly magnetostrictive particles in a different matrix material, as investigated by Clark and Belson[6] and by Sandlund *et al.*,[7] have the potential for maintaining adequate magnetostriction while meeting mechanical performance specifications. Herbst *et al.* have also studied $SmFe_2$/Fe and $SmFe_2$/Al composites and described a model to predict the magnetostriction.[8,9] Recently Nan has also proposed a mathematical model.[10]

In preliminary work magnetostrictive composites were fabricated consisting of highly magnetostrictive particles in a low magnetostriction, high permeability magnetic matrix with the objective of using the high permeability matrix to enhance the magnetic flux and hence the magnetostriction in the particles. The magnetostriction of these materials was measured at various field strengths and this produced unexpected low values.

An experimental study on magnetostriction of composites was undertaken using various matrix materials with different elastic moduli. Results indicated that the elastic modulus of the matrix has a significant effect on magnetostriction. The differences in bulk magnetostriction were investigated and, as a result of this, a model theory was developed and verified. This model theory was then used to predict the bulk magnetostriction of such composites.

The composites were prepared by blending powders in an argon atmosphere. The particulate magnetostrictive material used in this study was $Tb_{0.3}Dy_{0.7}Fe_2$ while the matrix materials consisted of metal and glass, the metals being Fe, Cu, Al, or $CeFe_2$. Blended powder was poured into a 6 mm diameter die, pressed at 1–3 kN under an inert argon atmosphere and heated at 10 °C/min to 300–600 °C depending on the matrix material. The load was removed and the material cooled to ambient temperature while still under argon atmosphere. Magnetostriction was measured using strain gauges. The magnetic field was applied parallel to the cylindrical axis of the specimens and the strain was measured along the same direction.

The magnetostriction model was based on the limiting assumptions of uniform stress or uniform strain in an inhomogeneous material. Beginning with the elastic properties, the model predicts that the elastic modulus should lie between two bounds based on these limiting assumptions.[11] The equations for the elastic modulus in the two cases are given below. The magnetostriction of the entire material was calculated in both instances, assuming that the stress in the whole material is generated only by the magnetostriction in the particles, scaled in proportion to the volume fraction of the particulate phase.

Assuming uniform strain throughout a composite material, the total stress in the linear regime over which Hooke's law applies, can be found from

$$\epsilon E_c = \epsilon E_t V_t + \epsilon E_m V_m , \tag{1}$$

where ϵ = strain, V = volume fraction, and E = elastic modulus. The subscript c indicates the whole composite, m indicates the matrix, t indicates the particulate magnetostrictive phase. Equating the strain throughout, the elastic modulus of the composite is given by

$$E_c = E_t V_t + E_m V_m . \tag{2}$$

Assuming that the stress throughout the material is uniform an alternative expression for the elastic modulus of a composite material is obtained. Again in the linear Hooke's law regime, uniform stress implies the product $E\epsilon$ must be the same for each component, therefore

$$\sigma = E_t \epsilon_t = E_m \epsilon_m , \tag{3}$$

where σ = stress. The strain throughout the entire material is given by

TABLE I. Measured and modeled saturation magnetostrictions of composites. Matrix materials were: A(Fe+glass), B(Cu+glass), C(Al+glass), D($CeFe_2$+glass), E(glass).

Sample	Vol. % components	Elastic modulus of matrix E_m (GPa)	Measured saturation magnetostriction $\lambda_e(10^{-6})$	Predicted magnetostriction Uniform strain $\lambda_{s\epsilon}(10^{-6})$	Predicted magnetostriction Uniform stress $\lambda_{s\sigma}(10^{-6})$
A	10/90 T+matrix A	149	15	20	26
B	10/90 T+matrix B	104	25	28	33
C	10/90 T+matrix C	65	55	46	48
D	10/90 T+matrix D	36	90	79	79
$E1$	10/90 T+matrix E	50	60	58	60
$E2$	30/70 T+matrix E	50	200	190	201
$E3$	60/40 T+matrix E	50	462	441	469
$E4$	80/20 T+matrix E	50	640	656	684
T	$Tb_{0.3}Dy_{0.7}Fe_2$	30	930		

$$\epsilon_c = \epsilon_t V_t + \epsilon_m V_m . \tag{4}$$

Substituting Eq. (3) into (4) gives

$$\epsilon_c = \frac{\sigma}{E_c} = \sigma \frac{V_t}{E_t} + \sigma \frac{V_m}{E_m} \tag{5}$$

and the elastic modulus is

$$E_c = \frac{1}{\dfrac{V_t}{E_t} + \dfrac{V_m}{E_m}}. \tag{6}$$

In the magnetostriction model it is assumed that the stress generated in the composite is caused entirely by the magnetostrictive phase and that the overall stress in the composite when it is magnetically saturated is the product of the volume fraction of magnetostrictive phase and the stress exerted by it. Under these conditions the following equation is obtained

$$E_c \lambda_s = E_t \lambda_{st} V_t , \tag{7}$$

where λ_s is the saturation magnetostriction of the entire material and λ_{st} is the saturation magnetostriction of the magnetostrictive phase alone. Substituting the expressions for the elastic modulus from Eqs. (2) and (6) gives limiting values of the saturation magnetostriction. For uniform strain a lower limit of magnetostriction is obtained, while for uniform stress an upper limit is obtained

$$\lambda_{s\epsilon} = \frac{E_t \lambda_{st} V_t}{E_t V_t + E_m V_m}, \tag{8}$$

$$\lambda_{s\sigma} = E_t \lambda_{st} V_t \left(\frac{V_t}{E_t} + \frac{V_m}{E_m} \right). \tag{9}$$

The saturation magnetostriction of a composite material should fall between the values of $\lambda_{s\epsilon}$ and $\lambda_{s\sigma}$ given by these equations.

Magnetostriction curves of two series of samples were measured in order to test these predictions. The first was a series of specimens with a fixed volume fraction of the same magnetostrictive phase in matrix materials with different elastic moduli. The second was a series of specimens with different volume fractions of the magnetostrictive phase in the same matrix material. This allowed the effects of the elastic modulus of the matrix and volume fraction of the magnetostrictive phase to be studied independently. The saturation magnetostriction and elastic moduli of both series of specimens are given in Table I. Magnetostriction curves of the first series of composite materials are shown in Fig. 1. These results show that the magnetostriction of the material increased with decreasing elastic modulus of the matrix. Results on the second series are shown in Fig. 2. These indicate that the saturation magnetostriction of the material increased with increasing volume fraction of the magnetostrictive phase.

A comparison of experimental measurements with model calculations based on Eqs. (8) and (9) is given in Fig. 3. The model calculations show the predicted magnetostrictions, as a function of the elastic modulus of the matrix, are in good agreement with measurements. For a two-component matrix (glass+metal), the value for elastic modulus of the matrix was calculated by averaging the limiting cases of the uniform strain value [Eq. (2)] and the uniform stress value [Eq. (6)]. The elastic modulus of the magnetostrictive phase was 30 GPa and that of the glass was 50 GPa as shown in Table I. Literature values were used for the elastic moduli of Fe, Cu, Al, and $CeFe_2$. The measured saturation magnetostriction decreased from 90×10^{-6} in a matrix with elastic modulus of 36 GPa to a value of 15×10^{-6} in a matrix with elastic modulus of 149 GPa. When the elastic moduli of the matrix and magnetostrictive phases were similar the pre-

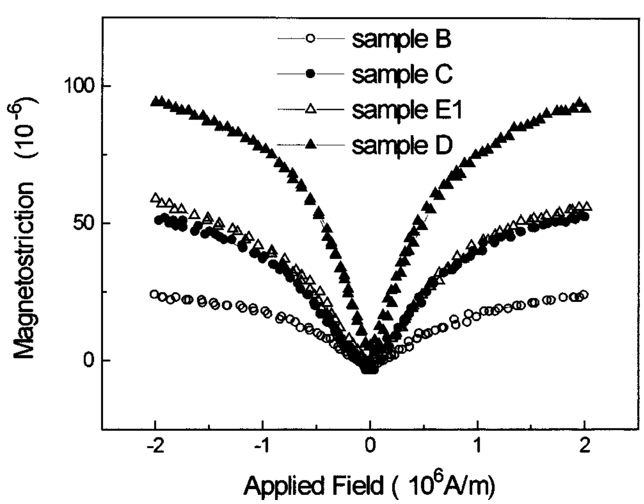

FIG. 1. Magnetostriction curves of several composites with equal volume fractions of magnetostrictive phase particles in different matrix materials. The elastic moduli of the different matrix materials are given in Table I.

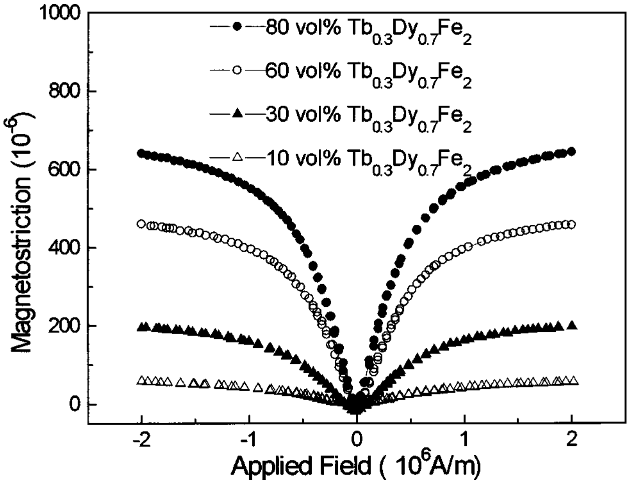

FIG. 2. Magnetostriction curves of several composites with different volume fractions of magnetostrictive phase properties in the same matrix material.

dicted limits for the saturation magnetostriction, $\lambda_{s\epsilon}$ and $\lambda_{s\sigma}$, were close in value, but the difference between these predicted limits increased with increasing difference between the moduli of the matrix and magnetostrictive phases. These results suggest that the elastic modulus of the matrix material has a significant impact on the saturation magnetostriction of composites, with a lower matrix modulus leading to higher bulk magnetostriction.

Model calculations were performed to obtain the magnetostriction as a function of the volume fraction of magnetostrictive phase using the same elastic modulus values of 30 GPa for the magnetostrictive phase and 50 GPa for the matrix. The results are compared with experimental measurements on a series of materials with the same values of matrix elastic moduli as shown in Fig. 4. In this figure, the solid line represents the modeled results based on the assumption of uniform stress and the dotted line represents the modeled results based on the assumption of uniform strain.

The model developed in the present work predicts that the magnetostriction of these composites should fall between an upper limit (based on uniform stress) and a lower limit

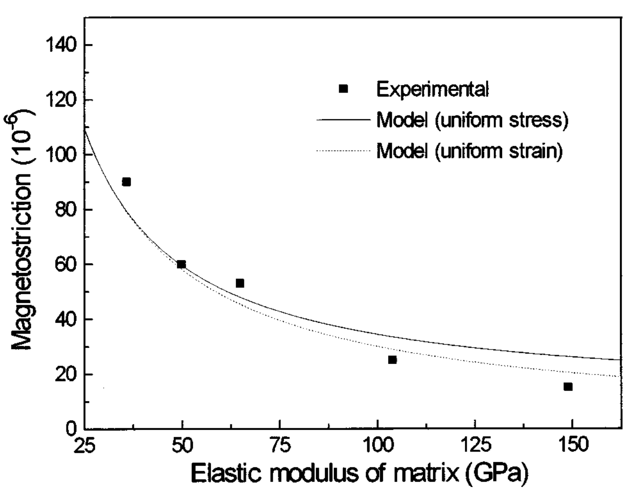

FIG. 3. Measured and modeled results of composites with fixed volume fraction of magnetostrictive phase and different matrix materials. Symbols are experimental measurement results at $H=2\times10^6$ A/m on materials with given values of matrix elastic modulus. The curves are model predictions for the uniform stress approximation and the uniform strain approximation.

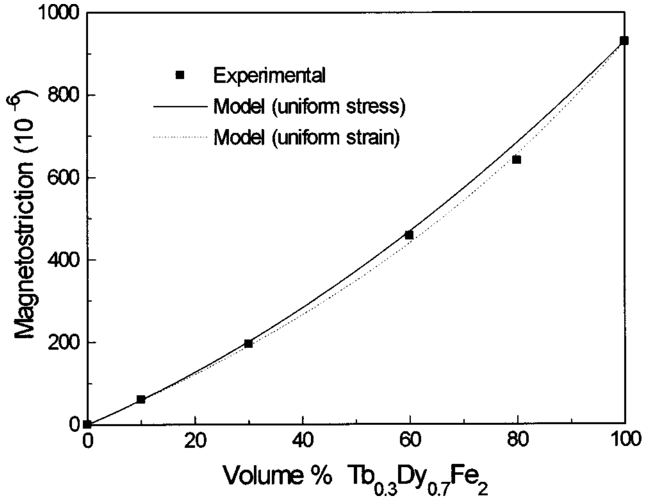

FIG. 4. Measured and modeled results for magnetostriction of composites with a matrix phase of known elastic modulus and different volume fractions of magnetostrictive phase. Measurements were made at $H=2\times10^6$ A/m. Model calculations were made using $E_t=30$ GPa, and $E_m=50$ GPa.

(based on uniform strain). The calculated magnetostrictions obtained on the basis of this model are in good agreement with the experimental results. In both experimental measurements and modeling the elastic modulus of the matrix seems to play a significant role in determining the bulk magnetostriction of a composite. Specifically the results show that the lower the elastic modulus of the matrix the higher the bulk magnetostriction of the composite. In practical terms the elastic modulus of the matrix cannot be too low without adversely affecting the mechanical performance of the material as a whole. In fact matching the elastic moduli of the matrix material and the magnetostrictive phase is probably the way to optimize this situation and obtain the necessary high bulk magnetostriction together with adequate mechanical properties for a magnetostrictive composite.

Ames Laboratory is operated by the U.S. Department of Energy by Iowa State University under Contract No. W-7405-ENG-82. This work was supported by the Office of Energy Research, Office of Computational and Technology Research, Advanced Energy Projects Division. The authors would like to thank the referee for calling attention to the work of C.-W. Nan, which was published after this letter was originally submitted.

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